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An Experimental and Theoretical Investigation of Turbulence Instabilities at Plasma-Magnetic Field Interfaces

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We enclose as part of this report the paper given at Belgrade in August and September 1965 at the International Conference on Ionization Phenomena in Gases. This paper summarizes a large part of the research we have done on the turbulence instabilities in plasma-magnetic field interfaces.

We have additional results to report on experiments with the plasma coaxial accelerator:

1. Short Plasma Coaxial Accelerator

   With a plasma coaxial accelerator with center conductor 3/4" in diameter and 1 3/4" long and outer conductor 2" in diameter, energized by a capacitor bank of 6 μf at voltages from 15 KV to 18 KV coupling loop measurements of the radial current density have been made. This coaxial accelerator exhibits the existence of well formed vortices following the current sheet when either polarity is applied to the center conductor. With a filling of hydrogen gas at 2000 microns pressure (2mm) the magnitude of the radial component of the diamagnetic current densities associated with the vortices is comparable with that of the current sheet itself. The experiment is now instrumented for measuring axial electric fields (E_z). Measurements are commencing on the measurement of the properties of the current sheet and the vortices as they proceed to contract at end of the center conductor.

2. Plasma Vortices in Plasma Flow over a Magnetic Dipole Coil

   Image converter photographs with both hydrogen and argon plasma flow over a magnetic dipole show clear evidence of the concentration of plasma in columnar vortices lined up with the magnetic field. These vortices are observed when the plasma flow is in the equatorial plane and also when the flow is parallel to the dipole axis.

3. Plasma Flow in a Coaxial Geometry

Photographs of the firing of a small two-wire plasma button gun into a B_θ produced by a coaxial system of copper conductors shows the trajectories of the plasma vortices as they are reflected from the magnetic field which increases as $\frac{1}{r}$. Work is proceeding to develop theoretical relationships which will explain the observed trajectories.

MEASUREMENT OF ROTATIONAL-VELOCITY AND ION-DENSITY PROFILES IN PLASMA VORTICES

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ABSTRACT

Floating double-probe measurements of the radial electric field E of a plasma eddy or vortex which rotates around dc magnetic field B gives the rotational velocity profile v, since E= -vxB. Measurements on vortices produced by the plasma coaxial accelerator /1,2,5/ and also by firing a small plasma gun /3,4/ across B, show that the radial electric field is proportional to the radial distance from the rotational center of the eddy. Thus, the eddies rotate as rigid bodies without shear.

1. Plasma Eddies Formed by Firing a Two-wire Button Gun Across a Homogeneous Magnetic Field.

The experimental arrangement shown in figure 1a gives the rotational velocity profiles of individual plasma eddies produced by a button gun. Double-probes drawing saturated positive ion current along B_z give simultaneously the ion density profiles. These measurements which cover peak ion densities from 10^{10} to 10^{12} ions/cm^3 show that the plasma eddy is an insular columnar plasma vortex rotating without shear around B_z. The experimental arrangement of figure 2 where a group of double probes is shown has enabled us to show that the plasma typically moves across the magnetic field in clusters of vortices. The pattern shown in figure 2a is the simplest of the clusters which have been observed.

The pattern of figure 2b is commonly observed. In figure 2 a barrier is used to permit only the plasma from the cathode to proceed across the magnetic field. This plasma is typically observed to give <u>two</u> resolvable illuminated areas upon striking the opposite wall which confirms the probe measurements that the plasma typically travels two vortices abreast. The peaked ion density at the centers of each of these two vortices abreast would be expected to produce the two illuminated areas. Figure 3 shows clearly the trajectories of these two photographically resolvable concentrations of plasma at the two vortex centers as they proceed from the cathode wire across the magnetic field. A group of thin plastic threads (a "harp") is used to enhance the illumination produced by the plasma. With a small two-wire copper plasma gun fired by .09 μf at 5 kv a magnetic field of 1500 gauss the vortex translational speed is $\sim 2 \times 10^6$ cm/sec, the vortex rotational speed at the periphery $\sim 10^6$ cm/sec and the ion density at the vortex center, 10 cm from the gun $\sim 2 \times 10^{12}$ ions/cm^3. In an apparatus which provides for the vortices to travel across a magnetic field for an extended distance the vortices can be observed to maintain their approximate shape and size for a travel distance of 40 cm (the limit of the size of apparatus). The vortices are apparently created at the gun in a fraction of a microsecond and are capable of enduring many microseconds.

2. <u>Plasma Eddies Formed in the Plasma Coaxial Accelerator.</u>

When the plasma coaxial accelerator is operated with the center conductor negative the leading edge of the current sheet is observed to be planar, i.e. perpendicular to the accelerator axis. If diameter of the center conductor is relatively small the magnetic field B_θ at the surface of the center conductor is much higher than at the other conductor. It can be shown[1] that such a plasma accelerator should develop large velocity shears across the magnetic field. Since the formation of plasma vortices relieves velocity shear we can expect plasma vortices to appear in such an accelerator and indeed they do, as figure 4 shows. In figure 4 the mass flow pattern has been constructed schematically from the measured traces of j_r, E_r, E_z. Here again the measured profiles of E_z indicate that the vortices rotate without shear and that the ion density is peaked at the center of the vortices. Here the peak ion densities for hydrogen in the accelerator for example are between 10^{14} and 5×10^{15}/cm^3. Typical velocities for the current sheath are 10^7cm/sec, and typical operating pressures with hydrogen are 100 microns to 1500 microns. Typical peak currents are 10^5 amp. with a corresponding magnetic field of 1.0 webers/m^2 at the surface of the center conductor. This accelerator is driven by a 300 μf capacitor bank operating at voltages between 1.5 and 2.5 kv.

An analysis of the two principal eddies shown in figure 5 shows that since the centrifugal drifts of the positive ions in the eddies is so much more important than that of the electrons, the diamagnetic current of the first eddy is carried by the positive ions (the eddy on the left) and by the electrons in the eddy on the right. For an eddy of radius r_o, peak ion density n_p, angular frequency ω, in an undisturbed magnetic field of B_o the kinetic energy of rotation per unit length can be expected to be

$$KE_{mech} \cong (\frac{1}{10}) \frac{1}{2} (\pi r_o^2) n_p m_i \omega^2 r_o^2.$$

The angular momentum $\Omega = (\frac{1}{10}) n_p m_i \omega r_o^2 (\pi r_o^2)$,

and the magnetic energy $\Delta E_{mag} \cong \frac{1}{2} \beta \, KE_{mech}$,

where $$\beta = \frac{KE_{mech}}{(B_o^2/8\pi) \pi r_o^2}.$$

In the parallel-plate accelerator it is possible to photograph with an image converter camera the plasma vortices, as shown in figure 6 of which there is a drawing in figure 7. Here the Hall effect gives a highly slanted current sheath.

3. Plasma Eddies Formed in a Dipole Magnetic Field.

If a small two-wire copper plasma gun is fired into the field of a magnetic dipole the plasma forms in slender vortices which are lined up along the magnetic field. Figure 8 shows an experimental technique for photographing these vortices. A screen made of fine nylon thread is illuminated when the plasma encounters it and renders a photograph of a portion of a plasma vortex which would otherwise not be visible. Figure 9 shows such a time exposure photograph with the plasma existing in four vortices which are lined up with the magnetic field. The location of the plasma in those isolated vortices is also observed with probes.

In a laboratory simulation of the solar-wind flow over the earths magnetosphere, a magnetic dipole has been placed in the broadside stream of plasma coming from an extended source essentially outside the dipole field. Figure 10 shows an image-converter photograph of the polar view of this plasma flow where the illumination from the plasma vortices can be seen. Figure 11 is a drawing which depicts the general shape of these vortices. Double probe measurements of electric fields show that the vortices also penetrate to the region inside the magnetic cavity formed by the plasma flow over the dipole. We suggest that these plasma vortices which penetrate to the interior of the magnetic cavity are the analogues of the Van Allen belts.

Figure 12 shows an image-converter photograph of plasma flow over a permanent magnet dipole (south polar view). A nylon thread screen or harp which intersects the equatorial plane on the windward side at about 45° to the equator is used to enhance the illumination from the plasma. The striated plasma pattern due to the formation of plasma vortices is clearly visible. The plasma here comes from a parallel plate plasma gun employing argon gas from a pulsed gas valve.

4. The Role of Plasma Vortices in Plasma Turbulence.

The foregoing results indicate that shear in plasma velocity across a magnetic field results in the formation of plasma vortices. The plasma is concentrated in the vortices and is essentially absent in the regions between the vortices. The vortices travel across magnetic fields two abreast analogous to the vortices in two dimensional fluid mechanics. These columnar vortices are undoubtedly the elements out of which plasma turbulence in an externally applied magnetic field is composed.

ACKNOWLEDGMENTS

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FIGURE CAPTIONS

Fig. 1 a. Experimental arrangement for measuring the rotational velocity profile $v_y(x)$ of plasma eddies produced by firing a small two-wire button copper plasma gun across a magnetic field B_z. b. and c. are typical profiles of v_y and n, the ion density, of an individual vortex (or eddy) which traverses the probes with a translational velocity v_t. b. and c. also show schematically the inferred circulation pattern for these vortices.

Fig. 2 Arrangement for exploring the patterns of vortex clusters which the plasma assumes as it proceeds across the magnetic field. a. and b. show schematically typical cluster patterns observed. A barrier is used to intercept the plasma from the anode so that only the plasma from the cathode moves across the magnetic field to the probes. This procedure produces a less complex cluster pattern.

Fig. 3 Time exposure photograph of trajectories of plasma vortices proceeding from only the cathode wire of a small two-wire plasma button gun. The concentration of plasma at the two vortex centers leaves two paths of illumination on the thin plastic threads which enhance the illumination produced by the plasma. The magnetic field is out of the photograph.

Fig. 4 Typical measured profiles for radial electric current density j_r, radial electric field E_r, axial electric field E_z and ion density n in the plasma coaxial accelerator. Vertical scales are arbitrary. a = .24 cm and b = 2.54 cm.

Fig. 5 Schematic relationship between j_r, E_z and E_r in the coaxial accelerator.

Fig. 6 Photograph of field-aligned vortices in the parallel plate accelerator operated in the static mode with hydrogen at a pressure of 200 microns.

Fig. 7 Drawing of Fig. 6.

Fig. 8 Set up of apparatus: dimensions of coil 18 mm I.D. x 35 mm O.D.; distance from gun to center of coil, 70 mm; distance from gun to center of screen 20 mm; screen inclined at 45°.

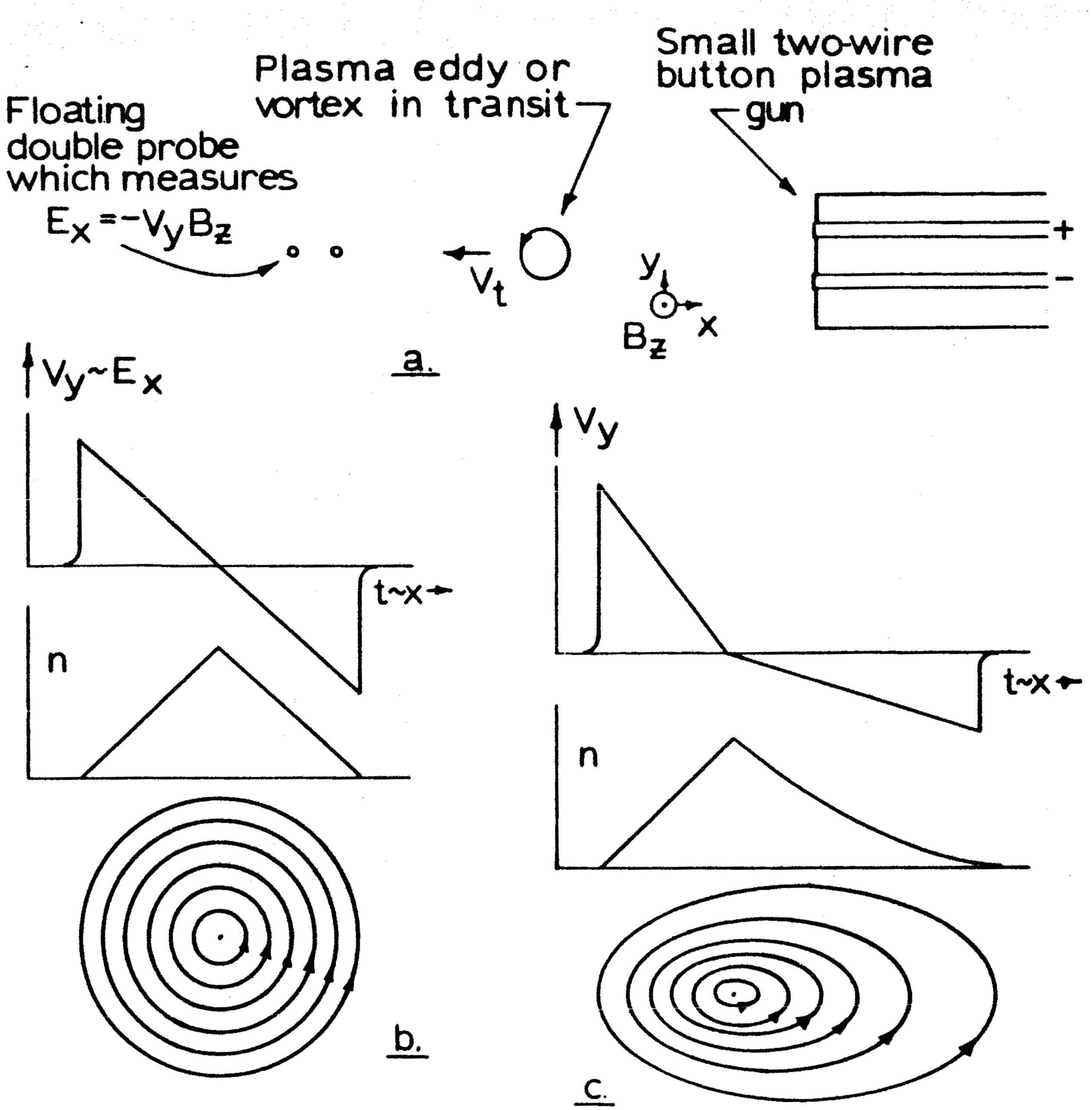
Fig. 9 Photograph showing the interception of the plasma by the nylon screen. Gun voltage 6 kv, (.3 μf capacitance). Gun current opposes external magnetic field.

FIGURE CAPTIONS (cont.)

Fig. 10 Image converter photograph (1 μsec exposure time) of the polar view of plasma flow over a 5-cm-diam. ring dipole. The battery of 5 copper button guns is 18 cm to the left of the coil. Time 6 μsec after start of gun firing.

Fig. 11 Sketch of a possible structure which would provide the effect seen in Fig. 1.

Fig. 12 Image converter photograph (0.3 exposure) of plasma flow over a permanent-magnet magnetic dipole (south polar view). The plasma flow is generated by a parallel plate plasma accelerator employing argon gas from a pulsed gas valve. The plasma is made visible by a harp of nylon threads the plane of which interesects the equatorial plane at an angle of 45°. The striated pattern produced by the plasma vortices is clearly visible. Plasma flows from the top. The photograph is taken at 20 μsec after beginning of firing of the gun. The plasma flow frum the gun endures about 15 μsec and the plasma takes 16 μsec to flow the 70 cm distance from the tip of the gun to the dipole.



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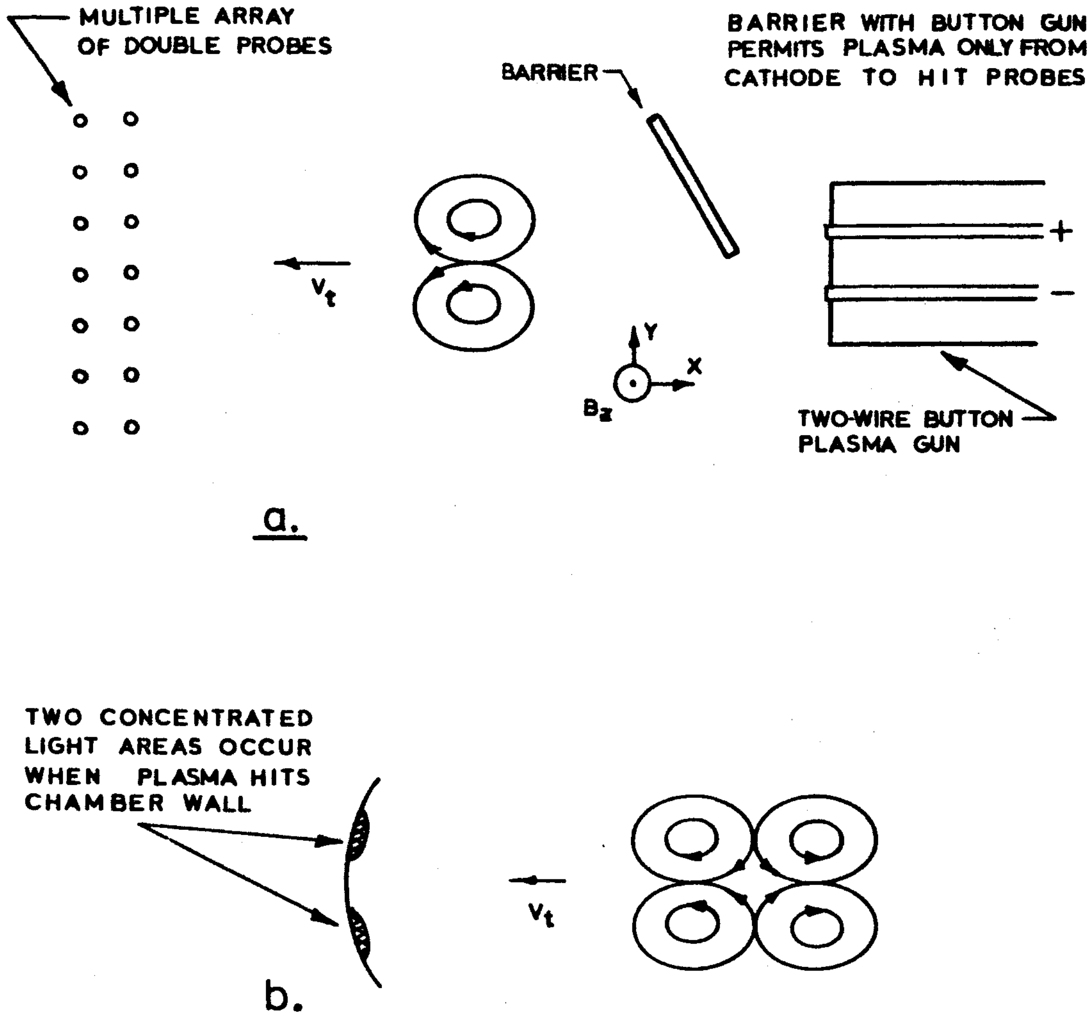

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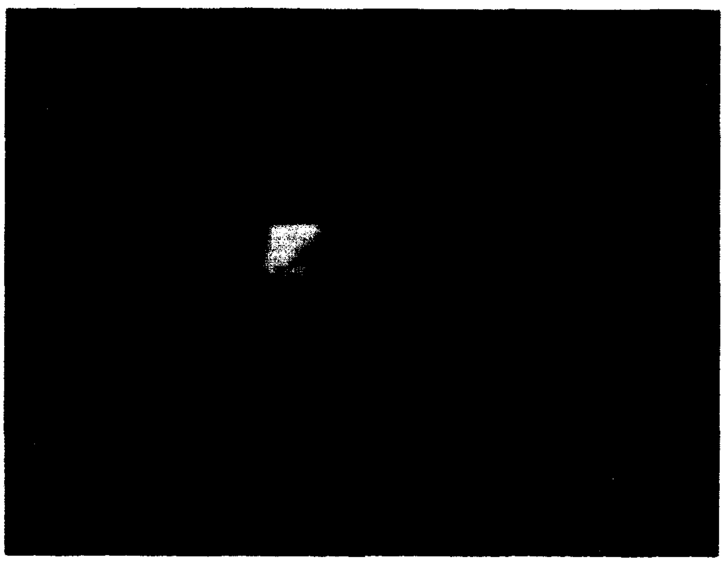

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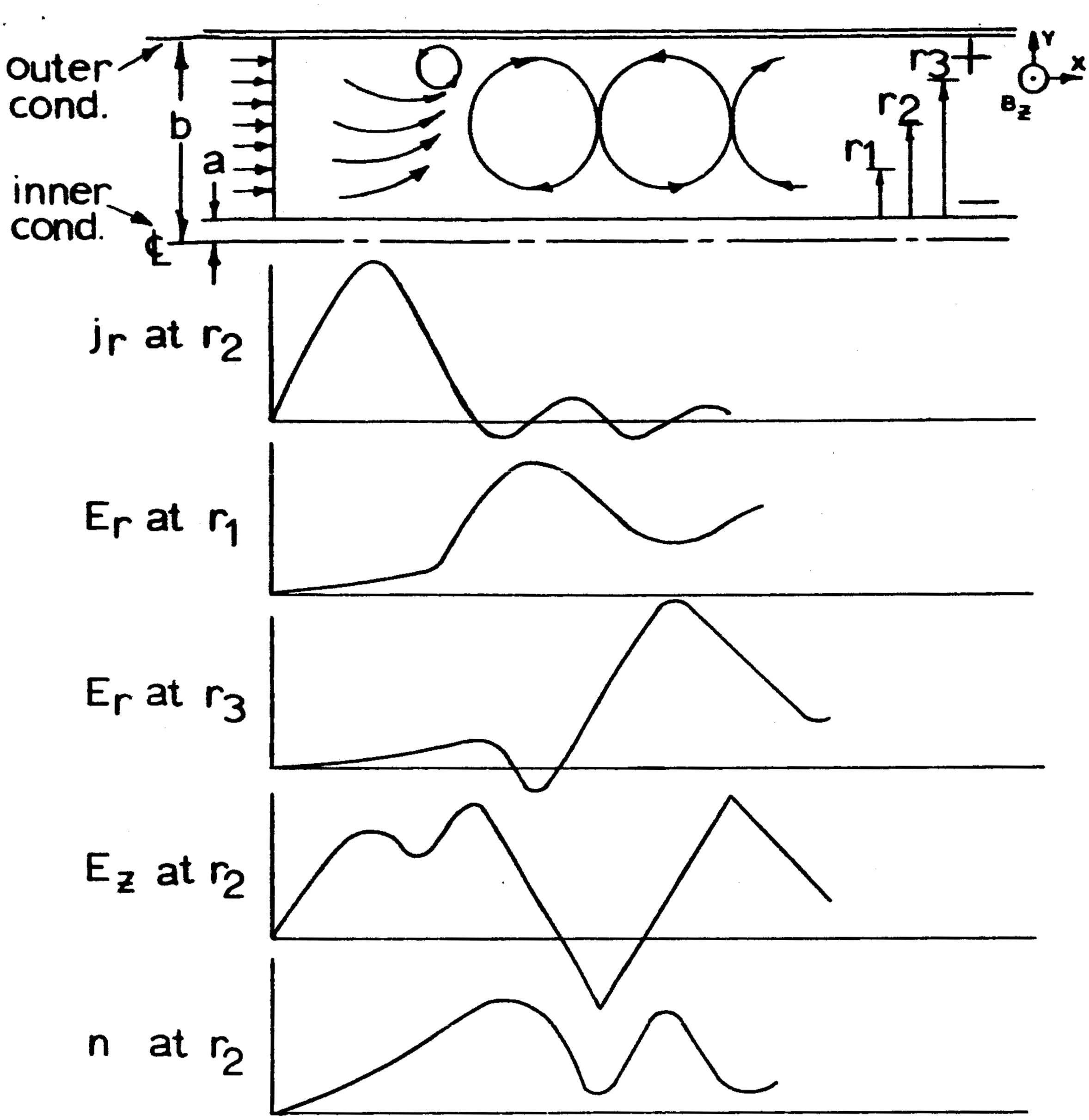

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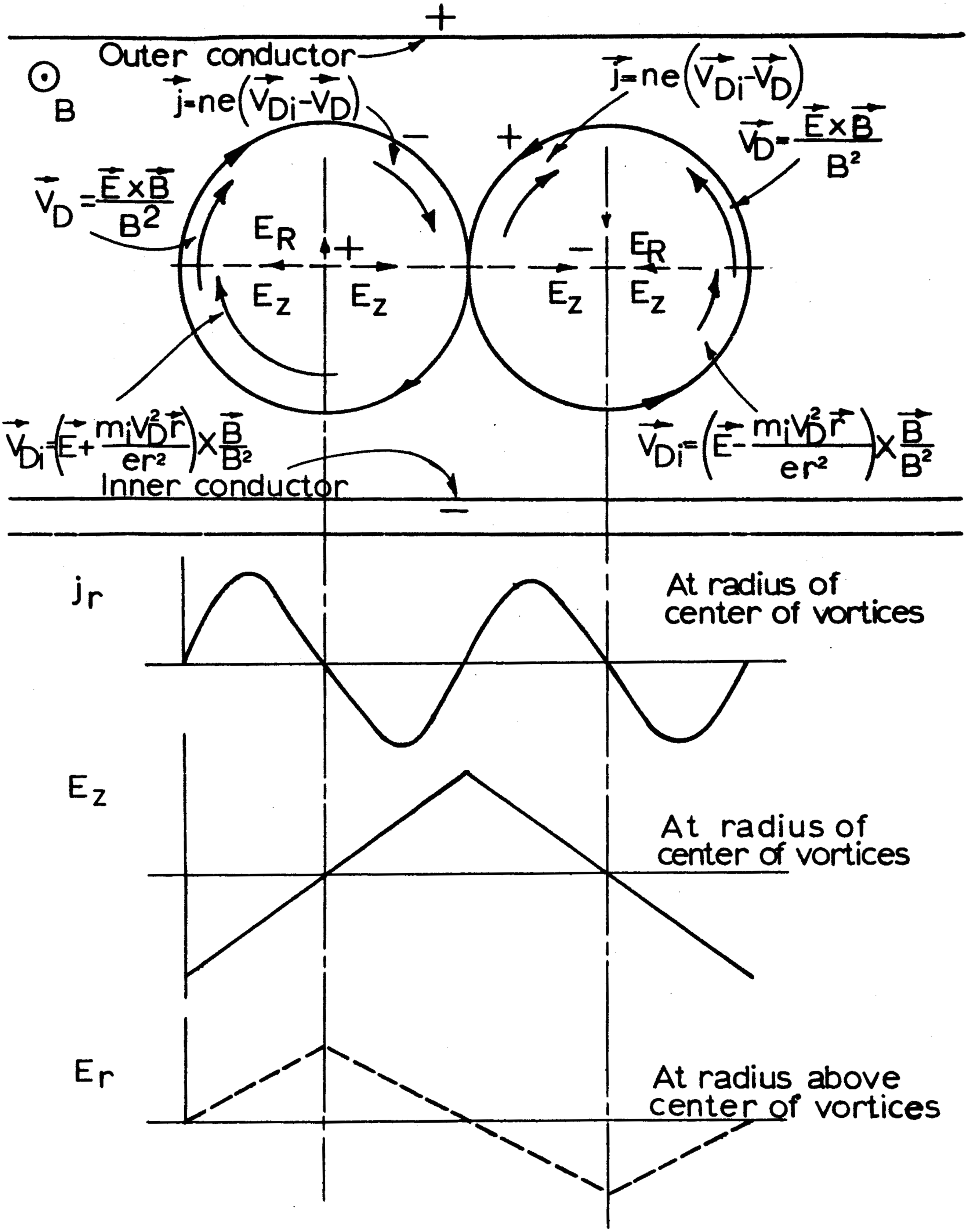
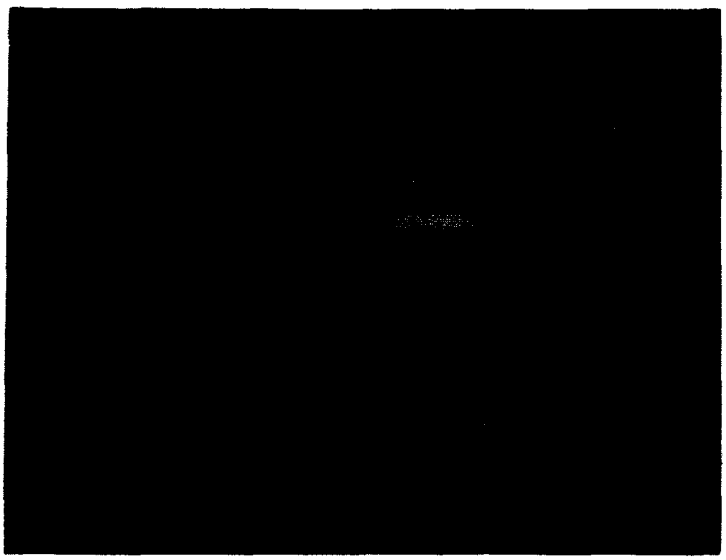


Fig. 5 Schematic relationship between j_r, E_z and E_r in the coaxial accelerator.



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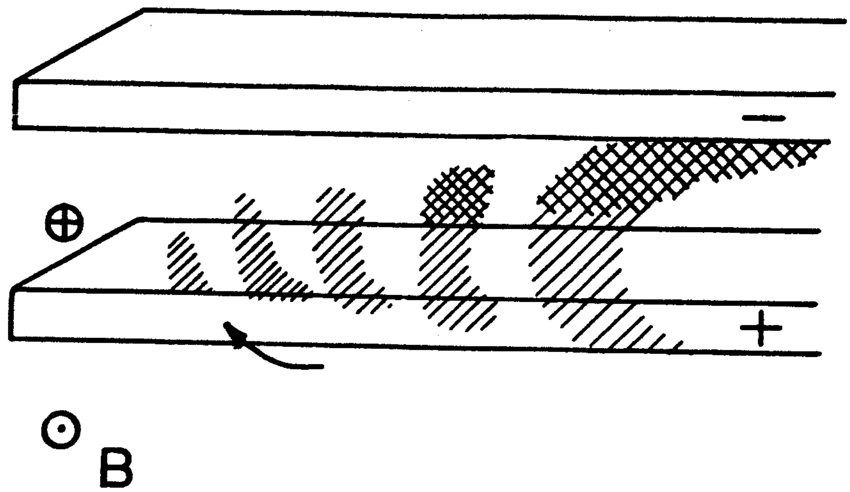

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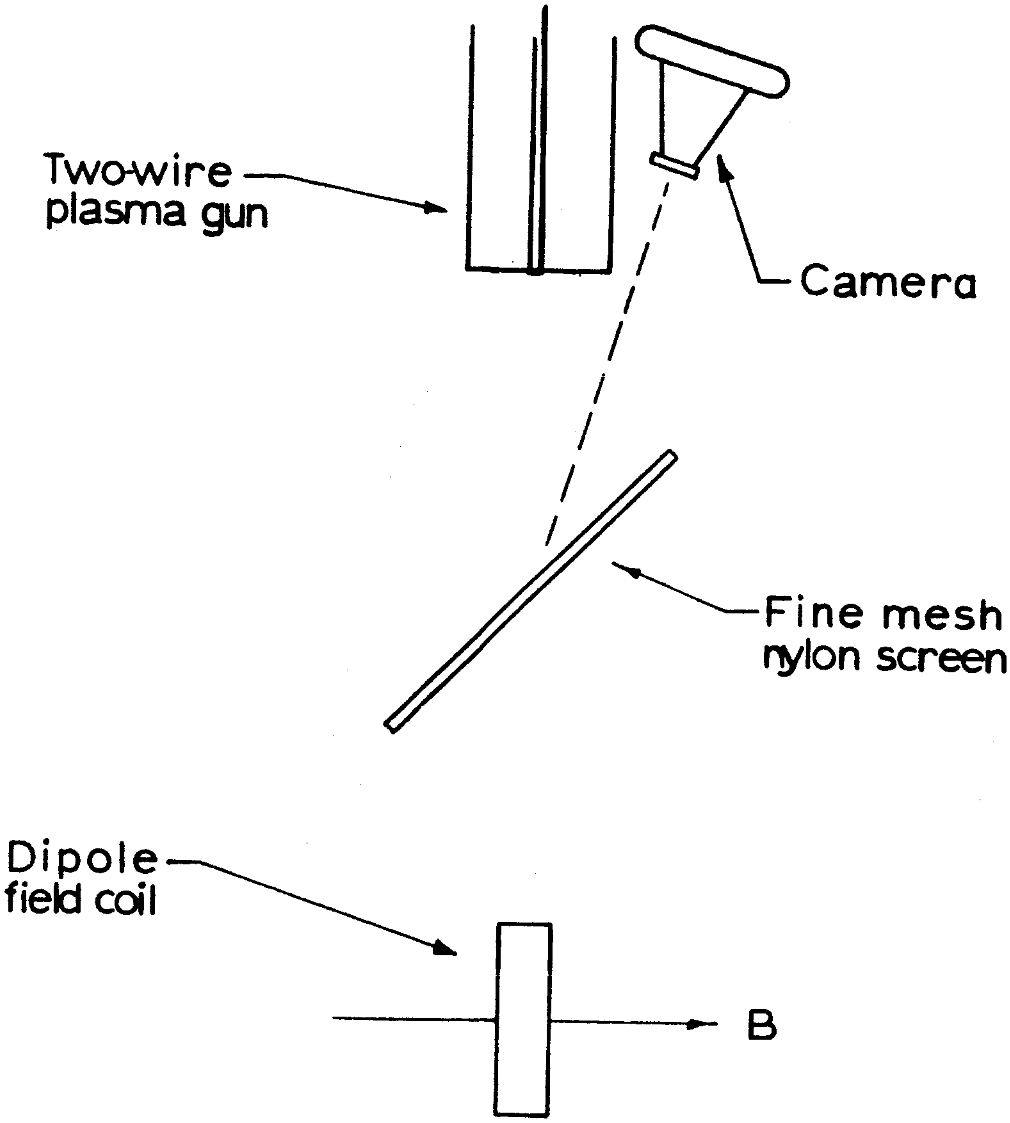

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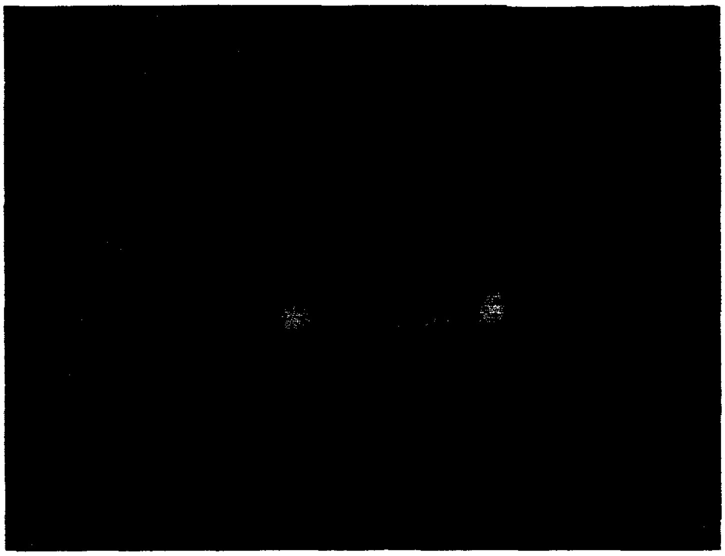

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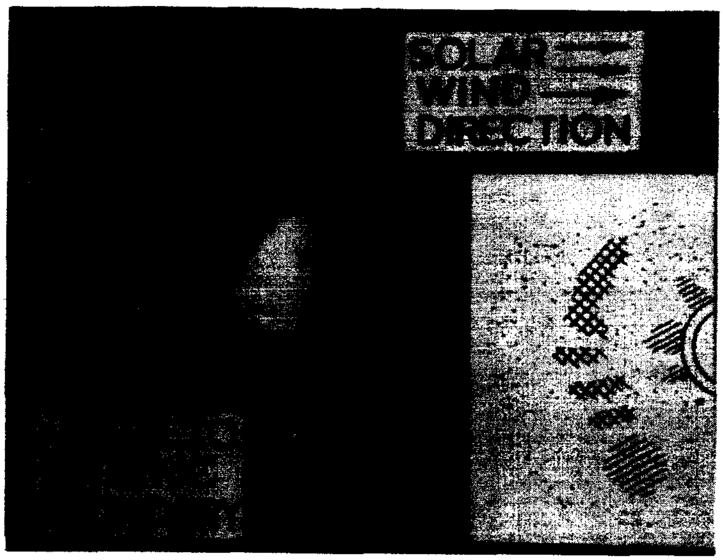

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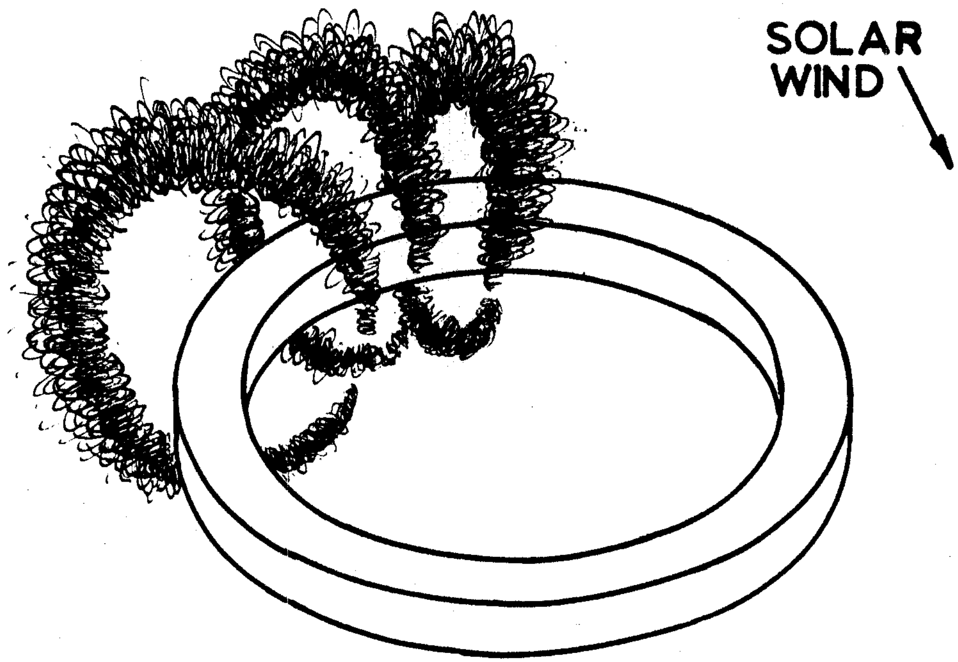

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